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Abstract

The radionuclides ^{14}C and ^{3}H may both be released from nuclear facilities. These radionuclides differ from most others in that they are isotopes of macro-elements which form the basis of animal tissues, feed and, in the case of ^{3}H, water. There are few published values describing the transfer of ^{3}H and ^{14}C from feed to animal derived food products. Approaches are described which enable the prediction of ^{14}C and ^{3}H transfer parameter values from readily available information on the stable H or C concentration of animal feeds, tissues and milk, water turnover rates, and feed intakes and digestibilities. It is recommended that the concentration ratio between feed and animal product activity concentrations be used as it is less variable than the transfer coefficient (ratio between radionuclide activity concentration in animal milk or tissue to the daily intake of a radionuclide).

Keywords: Carbon-14, tritium, milk, meat, eggs, concentration ratio, transfer coefficient

1. Introduction

Whilst the transfer of radionuclides to farm animal products has been the focus of many reviews (e.g. NRPB, 2003; USNRC 2003) these either largely neglect ^{3}H and ^{14}C, or give them brief consideration (e.g. IAEA 1994). In this paper we review equilibrium transfer parameters for ^{3}H and ^{14}C based on data or models with uncertainty ranges and a discussion of the effects of diet and production. An aim of the paper is to provide input into the revision of the International Atomic Energy Agency's *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments (TRS-364)* (IAEA 1994; Santucci & Voigt 2005).

1.1 Peculiarities of ^{3}H and ^{14}C transfer to animal products

Compared to most other radionuclides the predominant factor which makes ^{3}H and ^{14}C special is that they are radioactive isotopes of essential macro-elements which constitute the building blocks of animal tissues and feed components. The predominant form of ^{14}C released from nuclear installations is $^{14}CO_2$. Depending upon reactor type, other chemical form such as hydrocarbons (e.g. $^{14}CH_4$), ^{14}CO and carbonyl sulphide (^{14}COS) (Thorne, 2003) are also emitted. These other forms of ^{14}C are unlikely to require special consideration with regard to animal metabolism because plants and soil micro-organisms convert ^{14}CO, $^{14}CH_4$ and ^{14}COS to $^{14}CO_2$ (Maul et al, 2005). However, Howard et al (submitted) have recently demonstrated that ^{35}S ingested by dairy goats as COS^{35} was metabolised differently to other forms of ^{35}S administered.

The predominant forms of tritium released by nuclear facilities are tritiated water (HTO) and gas (HT). Approximately 10% of atmospheric tritium discharges from heavy water reactors are as HT with small amounts of tritiated hydrocarbons (IR-2003). Other nuclear facilities emit predominantly HT (Murphy 1992) and radiochemical factories can have significant liquid release in organic forms (Leonard 2001). Tritium gas is converted to tritiated water by soil bacteria. Organic forms of tritium, as released by radiochemical factories, are generally persistent in the environment.

Through photosynthesis and other metabolic processes, plants convert HTO and $^{14}CO_2$ into various organic compounds, predominately carbohydrates, protein and, to a lesser extent, lipids. Metabolic processes in animals transform plant organic compounds to different animal organic compounds; the composition of animal tissues is predominantly lipids and protein with some carbohydrates. Organic tritium exists as exchangeable and non-exchangeable forms. Exchangeable organic tritium is bound to hydrogen, nitrogen or sulphur in chemical groups that can dissociate and exchange rapidly with tritium in the HTO pool (Diabate, 1993; Belot et al, 1996). Therefore, exchangeable organic tritium has similar properties to HTO and can be considered to be part of the HTO pool. Non-exchangeable, or organically bound tritium (OBT), is carbon-bound tritium formed through biological processes in plants and animals. Organically bound tritium is radiologically important because it has a considerably longer retention time in the body than HTO (Diabate 1993)..

At equilibrium, about 99 % of the dose to humans from ^{14}C is via ingestion with only approximately 1 % from inhalation (Holtum, 1986). Similarly, when considering transfer to farm animals, inhalation, and drinking water, can generally be ignored as a source of ^{14}C (Thorne 2003). Consequently, the transfer from organic carbon in feed to animal products is the only pathway that needs to be taken into account. The transfer of tritium is more complicated, because intakes may be from HTO (in drinking water or feed), from OBT in feed, or inhalation of HTO and HT. Tritium (from HTO) can also be absorbed through the skin. Animals ingesting contaminated vegetation will metabolise ^{14}C and OBT for maintenance energy, growth or production. Both tritium and carbon are transferred through the environment without bioaccumulation in any compartment (Brown et al, 1996), and concentrations in the environment for chronic releases are most easily estimated using a specific activity approach (Evans 1969). This assumes that the specific activity, $^{3}H/^{1}H$ or $^{14}C/^{12}C$, in all environmental compartments is the same at a specified location. Specific activity assumptions, which are used in many regulatory models, result in upper estimates because complete equilibrium in all environmental compartments is unlikely to be attained. For tritium, alternative approaches, taking into account differences between HTO and OBT have been proposed to model transfer to animal derived food products (Galeriu, 1994; Galeriu et al, 2001; Peterson et al, 2002).

2. Equilibrium transfer parameters

The main difficulty in providing recommended transfer parameter for ^{3}H and ^{14}C is the paucity of relevant experimental data with the exception of the transfer to cows milk following ingestion of HTO (see review by Thorne et al 2001). Consequently, modelling approaches and specific activity assumptions have to be relied upon.

The transfer of radionuclides from diet to animal derived food products has for many years been expressed as the equilibrium transfer coefficient (F_f for meat; F_m for milk) (Ward et al. 1965) which is the fraction of daily activity intake appearing in 1 kg (or 1 l) of animal product:

$$F_{f(m)} = \frac{C_{ap}}{A} = \frac{C_{ap}}{C_f * Q_f} \qquad [1]$$

where:

C_{ap} - concentration of tritium or ^{14}C in animal produce (Bq kg^{-1} fresh weight (fw)

A - daily radionuclide intake (Bq d^{-1})

C_f - concentration of tritium or ^{14}C in animal feed (Bq kg^{-1} fw)

Q_f - daily feed consumption (kg fw d^{-1}).

C_f and Q_f, both can also be defined in dry matter units (Bq kg^{-1}dm, kg dm d^{-1}, respectively).

Some authors have suggested that a simple transfer ratio (CR) may be more appropriate especially when considering homeostatically controlled macro-elements such as ^{3}H and ^{14}C (Galeriu et al. 2001; Howard et al. submitted):

$$CR = \frac{C_{ap}}{C_f} = F \cdot Q_f \qquad [2]$$

Table 1 presents a summary of previously recommend transfer coefficients (USNRC, 1977; CSA 1987; GRG, 1990; IAEA 1994) for ^{14}C and ^{3}H from dietary HTO. In addition, because of the importance of OBT to dose, the IAEA (1994) also recommended transfer factors for the milk and meat of goats after OBT feeding. Table 1 demonstrates the absence of many values for animal products. In this paper a more complete list of transfer parameters is proposed; this list includes potential ranges for the transfer parameters which are based on specific activity approaches, the small amount of experimental data that is available and approaches used in recently proposed models.

2.1 Carbon-14

The majority of carbon intake by farm animals is in organic forms and the same will be true for ^{14}C. The carbon intake from feed is between 10 and 20 g C d^{-1} kg^{-1} per kg of body weight, whilst the retention from inhaled carbon dioxide is less than 0.2 mg C d^{-1} kg^{-1} (Watkins et al 1998) and that drinking water less than 2 mg C d^{-1} kg^{-1}. In both feed and animal tissues, inorganic carbon is less than 1 % of the total carbon. Consequently, in modelling ^{14}C transfer we need only to consider the transfer of organic carbon using the dry matter intake, and dry matter concentrations of organic ^{14}C and ^{12}C. Applying the specific activity approach (to give conservative estimates) to Equation (1) we obtain:

$$F' = \frac{C_{ap}}{C_{f\,dm} * Q_{fdm}} = \frac{C^{C}_{ap}}{C^{C}_{fdm} * Q_{fdm}} \qquad [3]$$

where:

C_{ap} - concentration of ^{14}C in animal produce (Bq kg^{-1} fresh weight)

C^{C}_{ap} - concentration of C in animal produce (kg kg^{-1} fresh weight)

C_{fdm} - concentration of ^{14}C in animal feed (Bq kg^{-1} dry matter)

C^{C}_{fdm} - concentration of C in animal feed (kg kg^{-1} dry matter)

Q_{fdm} - daily feed consumption of animal (kg DM d^{-1})

The composition of animals diets can vary considerably, but the carbon content per kg dry matter (DM) shows less variability (Tables 2 and 3). Table 4 presents typical carbon contents of animal products (Geigy 1981). Whilst this may vary depending on breed, level of nutrition, diet composition and meat quality, variation is not large; coefficients of variation are characteristically < 10 % for egg, about 10 % for milk and up to 30 % for meat (Geigy, 1981, McDonald et al, 1995).

Daily animal feed intake has a large variability due to breed, diet quality, production level and environment. There are differences between highly efficient agricultural systems compared with subsistence farming. For example a sheep of similar mass and growth rate can consume twice the mass of food from mountain rangeland than it does when stabled. (Freer et al, 2002). A small cow with only 5 Ld^{-1} milk productions will consume about 8 kg dm of grass, but a large cow with 40 Ld^{-1} milk needs up to 25 kg dm d^{-1}. A high concentrate diet will reduce the feed intake compared with a diet of pasture grasses.

Using values presented in Tables 3 and 4, transfer coefficients for ^{14}C have been derived according to Equation (3) (Table 5). The typical live-weights, production rates and daily dry matter intake rates (based on average live-weight and moderate production rates according to practice in Europe and North America) assumed are also shown. Ranges in transfer coefficient have also been estimated for varying animal mass and production (which defines the intake rate of DM and hence C) over ranges applicable for temperate climates. Estimated transfer coefficients can be seen to vary by up to 5-fold depending upon the assumption made with regard to mass, production and diet; milk yield is the main contributor to variability. However, the concentration ratio, also shown in Table 5, is subject to less variation caused by most animal and dietary parameters. Because the coefficient of variation for the carbon content in animal food is less than 10 % and in animal products is generally 10-40 %, the concentration ratio range is estimated to vary by less than 25 % of the average values in Table 5. Concentration ratios are also more similar between species because they do not include dry matter intake (which varies considerably between species) in their derivation. This agrees with Table 4 which demonstrates that the carbon content of milk or meat does not vary greatly between species. Whilst transfer coefficients have previously been suggested by some organisations (e.g. Table 1) we propose that concentration ratios for ^{14}C should be used be instead, because concentration ratios are more robust and can be used reliably in diverse situations. Ranges of transfer factor and concentration ratios given in Table 5 apply also to extensive grazing systems and subsistence farming.

2.2 Tritium

As discussed above, ^{3}H can be ingested by animals as either, or typically both, HTO (food and drinking water) and organic matter, including OBT. Inhalation and skin absorption are also possible routes of HTO intake. Exchangeable organic tritium and HTO rapidly equilibrate with body water. Organically bound tritium from food is metabolised by animals and partially converted to HTO. Body HTO is also partially metabolised to OBT. Consequently, the equilibrium activity concentrations of HTO and OBT in animal products ([HTO] and [OBT] respectively) are given by:

$$[HTO] = F_{HH} I_{HTO} + F_{OH} I_{OBT} \qquad [4]$$

$$[OBT] = F_{HO} I_{HTO} + F_{OO} I_{OBT} \qquad [5]$$

Where: F_{HH} is the transfer coefficient from dietary HTO to product HTO (d kg^{-1}); F_{HO} is the transfer coefficient from dietary HTO to product OBT (d kg^{-1}); F_{OH} is the transfer coefficient from dietary OBT to product HTO (d kg^{-1}); F_{OO} is the transfer coefficient from dietary OBT to product OBT (d kg^{-1}); I_{OBT} and I_{HTO} are the daily intakes of OBT and HTO respectively (Bq d^{-1}).

Whilst the specific activity approach can be adapted to provide a simplified and conservative assessment (Peterson and Davis, 2002; Raskob, 1994), recently a model for tritium concentrations in animal products based on hydrogen metabolism was proposed (Galeriu et al., 2001). The model utilises parameters which are readily available and allows predictions to be made for any animal product (for which the parameters are available). The model equations are (the reader should refer to Galeriu et al. (2001) for the derivation of these):

$$F_{HH} = \frac{\nu_{tw}}{\nu_{Bw}\lambda_w M_B} \qquad [6]$$

$$F_{OH} = \frac{\nu_{tw} F_D}{\nu_{Bw}\lambda_w M_B} = F_{HH} F_D \qquad [7]$$

$$F_{HO} = \frac{SAR\, m_{ot}}{0.111 \nu_{Bw} M_B \lambda_w} \qquad [8]$$

$$F_{OO} = \frac{m_{ot} - F_{HO} I_{HHO}}{I_{OBH}} \qquad [9]$$

Where:

ν_{tw} is the fraction of tissue or pool, *t*, composed of water;

ν_{Bw} is the fraction of the whole body composed of water;

λ_w is a first order rate coefficient describing the body water turnover rate (d^{-1});

M_B is the animal's live-weight (kg)

F_D is the dry matter diet digestibility;

m_{ot} is the mass of organically bound hydrogen in 1 kg of tissue (kg kg^{-1});

I_{OBH} is the daily dietary intake of hydrogen in organic forms (kg d^{-1}) determined by the dry matter intake and composition;

I_{HHO} is the daily total intake of hydrogen as water (kg d^{-1})

SAR is the ratio of the specific activity of OBT in the animal product o the specific activity of HTO in the body water (the authors assumed a value of 0.25 for SAR based on the results from small monogastric animals)

and the constant 0.111 is the mass of hydrogen in water (kg kg^{-1})

The total water flux of animals, given by $\nu_{Bw} M_B \lambda_w$, includes drinking water, water from food, respiration, skin absorption and metabolic water. Ambient temperature influences dry matter and water intakes, whilst the activity level of an animal influences feed intake. Other variables, such as diet composition and breed, can be considered and the model can be applied to various climate and agricultural practices if specific input data are known.

When compared to available experimental data, there was good agreement for F_{HH}, F_{OH} and F_{OO} between the observed and predicted transfer coefficient values (see Figure 1). In the case of F_{HO} there was an under-prediction of about 25% which may have been due to the SAR value used (0.25) being derived from small mammal experiments whilst all the available observed data were for ruminants. The discrepancy may be due to the higher carbohydrate digestion and rumen bacterial activity of ruminants. However, this disagreement is likely to be of little importance because the pathway from HTO to OBT makes only a small contribution to a tissue's overall ^{3}H content. Tables 6 and 7 present tritium transfer coefficients (for temperate climates) and ranges using the model of Galeriu et al. and the same assumptions for animal mass and production level as in the case of ^{14}C (i.e. Table 5); Tables 2 to 4 present data on the hydrogen contents of animal tissues and feeds used. Ranges were assessed considering animal mass, production level and diet variability under European conditions. For example, if straw are only used for cows, this will decrease the transfer coefficients to milk compared with a grass only diet.

In Tables 6 and 7 we present total tritium transfer coefficients after intakes of HTO ($F_{HTO}=F_{HH}+F_{HO}$) or OBT ($F_{OBT}=F_{OH}+F_{OO}$). The fraction of OBT in animal produce was estimated as F_{HO}/ F_{HTO} or F_{OO}/ F_{OBT}.

To apply the concentration ratio in the case of tritium we have to address the occurrence of HTO and OBT in both intake and product:

$$CR_{HTO}=(F_{HH}+F_{HO})* I_w \quad [10]$$

$$CR_{OBT}=(F_{OH}+F_{OO})*I_{dm} \quad [11]$$

Where I_w is the total water intake (including drinking water and water from food) and I_{dm} is the total dry matter intake

When the CR approach is used, the concentration of HTO in intake water must refer to total water and not only to drinking water.

From equations 4-11 we obtain

$$CR_{HTO}=\nu_{tw}+SAR* m_{ot} \quad [12]$$

$$CR_{OBT}=(\nu_{tw}*FD)*I_{dm}/(I_w) +(m_{ot}-SAR* m_{ot})/C_{oh} \quad [13]$$

With C_{oh} the concentration of organic hydrogen in the animal diet (kg kg^{-1}dm).

Galeriu et al. (2001, 2003) also performed a limited sensitivity analysis varying input parameters within known ranges (Table 8). For dairy cows the parameter which resulted in the greatest variation in estimated transfer coefficients was milk yield, as in the case for ^{14}C. Water intake and food digestibility may be sources of uncertainty if specific information is missing.

In the above assessment we used the metabolic model of Galeriu et al (2001), because the model better takes into account the formation of OBT in animal products and, if input information is available, can be applied to various environments and animal managements regimes. Alternate models have also been published, based on specific activity approaches and considering OBT. NEWTRIT (Peterson and Davis 2002), a model formulated in terms of the tritium-to-hydrogen ratio in each environmental compartment, predicts concentrations of HTO and OBT in animal products, for a generic diet and has been used for compliance assessment by the US Environmental Protection Agency. An animal model based on water balance between intake and animal product is found in DCART (Peterson, 2004) and applied under Californian conditions. Both NEWTRIT and DCART consider all pathways for water intake (drinking water, food, metabolic, respiration) and mixed diets (of pasture, hay and grains). In DCART, the transfer to OBT in animal produce is addressed with some simplified assumptions concerning the role of OBT. When predictions of the Galeriu et al model were compared with probabilistic results from DCART (Peterson 2004), the deterministic (Galeriu et al) results are within the DCART predicted ranges (Figure 2).

In a deterministic comparison between the metabolic model and DCART, with the same input for both models, the only significant difference is the concentration of OBT in animal products, DCART giving lower values up to 50 %. DCART is a user-friendly spreadsheet model that assesses dose to the public for routine tritium emissions. DCART's atmosphere-soil-plant pathways have been validated in many practical assessments (see Peterson 2004). DCART's underestimate of concentrations of OBT in animal products contributes little to the uncertainty in the total dose.

The approach presented by Galeriu et al has also been used to derive concentration ratios in Tables 6 to 8. As was seen for ^{14}C, concentration ratios for tritium are less dependent on input parameters than transfer coefficients (Table 8), although food digestibility is important to the OBT concentration ratio. Concentration ratios, again like ^{14}C, are also more similar between species (Tables 6 and 7) than are transfer coefficients. Consequently, CR values describing ^{3}H transfer to animal products are recommended over transfer coefficients.

3. Discussion

Using the approaches outlined above ^{3}H and ^{14}C concentration ratios can be relatively easily predicted for animals other than those typical of North American and European conditions. For example CR for ^{14}C in horse milk and meat of about 0.11 and 0.33, respectively, are estimated, using available animal metabolism information (Geigy 1981, Stoica 1995, Minesota 2006**)**. These values are slightly lower than for other farm animals in Table 5, reflecting lower fat content. Preliminary values for tritium CR in horse milk, (CR_{HTO}=0.9, CR_{OBT}=0.33), (Table 9), are not very different from other animals. For horse meat the preliminary CR given in Table 9, are similar to the values in Tables 6 and 7. CR values for the horse can vary due to different environmental conditions and grazing practices, but because the variability in CR is not too high, the above values can be recommended as default values.

In Asia yak are specific domesticated mammals, living at high altitude, under adverse environmental conditions. Yak milk has a comparatively high fat content (ILRI 2006a), close with sheep milk. In contrast to the yak, the camel is adapted for deserts. Concentration ratios estimated for ^{3}H and ^{14}C to yak and camel products using available metabolic information (FAO 2006, ILRI 2006 b) are presented in Table 9. These values are similar to those estimated for more common farm animals as can be seen in Tables 5 – 7.

Whilst not exhaustively considering all production systems the methodology described above appears to provide values useful for applications in screening models. However, the assumptions of equilibrium is unlikely to be valid in many instances (e.g. if half-times are comparable or longer than the period from weaning to sacrifice). Available dynamic approaches to modelling the transfer of farm animals will be considered in a further paper.

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Figure legends

Fig. 1: Comparison between predicted log (transfer coefficient) with experimentally observed log (transfer coefficient) from Galeriu et al 2001. Solid line is the 1:1 relationship, dotted line is the line of best through the data ($y = 1.1x + 0.14$; $R^2=0.98$). Experimental data include values of F_{HH}, F_{HO}, F_{OH}, F_{OO} for cow and goat milk, beef, veal, pork and goat meat.

Fig. 2: Deterministic concentrations of HTO and OBT in animal products predicted by the Galeriu et al (2001) metabolic model lie within the 95 percent confidence interval of concentrations predicted by DCART

Table 1

Previously recommended transfer coefficients for ^{14}C and ^{3}H from dietary HTO

Product	^{14}C			^{3}H			
	USNRC[1]	CSA[2]	GRG[3]	USNRC[1]	CSA[2]	GRG[3]	IAEA[4]
Milk (d l^{-1})							
Cow	1.2×10^{-2}	1.5×10^{-2}	4.0×10^{-2}	1.0×10^{-2}	1.4×10^{-2}	2.0×10^{-2}	1.7×10^{-2}
Goat	1.0×10^{-1}			1.7×10^{-2}			
Meat (d kg^{-1})							
Unspecified	3.1×10^{-2}		2.0×10^{-2}	1.2×10^{-2}		2.0×10^{-2}	
Beef		6.4×10^{-2}			1.8×10^{-2}		
Pork		1.8×10^{-1}			7.4×10^{-2}		
Poultry		4.2			3.5		
Eggs (d kg^{-1})		3.1			2.2		

[1]USNRC, 1977; [2]CSA 1987; [3]GRG, 1990; [4]IAEA 1994

Table 2

Hydrogen and carbon as fractional content of basic constituents of food and animal products (Diabate, 1993).

Food constituent	Free H	Organically bound H	Total organic H*	C
Water	0.11	0	0	0
Carbohydrate		0.044	0.064	0.44
Protein		0.051	0.068	0.52
Lipids		0.117	0.12	0.77

* include exchangeable and non- exchangeable (OBH) organic hydrogen

Table 3

Carbon and organic hydrogen contents of some common animal foods (Stoica, 1997, McDonald et al, 1995).

Food	C content kg C kg^{-1} DM	CV[+]	Organic H content kg H kg^{-1} DM	CV[+]
Grasses	0.42	0.03	0.06	0.03
Hay	0.42	0.01	0.06	0.02
Silage[1]	0.40	0.09	0.06	0.07
Roots	0.41	0.05	0.06	0.04
Cereals	0.46	0.06	0.07	0.05

[+]Coefficient of variation; [1]Values representative of grass or maize silage

Table 4

Typical hydrogen and carbon contents of animal products (kg H or kg C per kg fw) (Geigy, 1981).

Animal product	Free H	Organically bound H	Total organic H	C
Milk				
Cow	0.096	0.008	0.010	0.067
Sheep	0.090	0.014	0.016	0.107
Goat	0.095	0.009	0.010	0.070
Meat				
Beef	0.077	0.022	0.025	0.178
Veal	0.077	0.021	0.024	0.173
Mutton	0.074	0.026	0.029	0.203
Lamb	0.077	0.021	0.025	0.176
Goat	0.077	0.021	0.024	0.172
Pork	0.066	0.034	0.038	0.258
Hen	0.077	0.022	0.025	0.178
Chicken	0.080	0.019	0.022	0.155
Egg	0.074	0.018	0.021	0.142

Table 5

Derived transfer coefficients and concentration ratios* for ^{14}C. Estimates are for typical live-weights

Product	Live-weight (kg)	Production rate (l d^{-1} or kg d^{-1})	Dietary intake (kg DM d^{-1})	F_m (d l^{-1}) or F_f (d kg^{-1})	F_m or F_f range	CR	CR range
Milk							
Cow	550	15	14	0.011	0.005-0.024	0.16	0.13-0.2
Sheep	50	1.3	1.8	0.142	0.05-0.2	0.25	0.22-0.3
Goat	50	2.5	2.5	0.067	0.04-0.12	0.17	0.13-0.21
Meat+							
Beef	500	0.7	9.3	0.046	0.03-0.09	0.42	0.33-0.6
Veal	160	0.8	4.9	0.085	0.06-0.15	0.41	0.3-0.5
Mutton	50	0.08	1.2	0.396	0.2-0.5	0.48	0.4-0.52
Lamb	20	0.2	1	0.419	0.3-0.6	0.42	0.36-0.48
Goat	50	0.08	1.2	0.341	0.2-0.5	0.41	0.35-0.45
Pork	100	0.8	2.7	0.228	0.15-0.4	0.61	0.4-0.73
Hen	2.5	0.007	0.12	3.532	3-4	0.42	0.3-0.45
Chicken	1.7	0.03	0.11	3.355	3-5	0.37	0.33-0.43
Egg	2.5	0.05	0.15	2.195	2-3.3	0.34	0.31-0.4

*Concentration ratio use concentration in animal product fresh and dry matter feed (as per Equation 2); +Estimates for meat are for animals at typical slaughter weights.

Table 6

Transfer coefficients for HTO intake estimated using the approach of Galeriu et al. (2001).

Animal product	*F_{HTO} d l^{-1} or d kg^{-1}*	*Fraction OBT*	*F_{HTO} range*	*CR_{HTO}*	*CR_{HTO} range*
Cow milk	0.014	0.04	0.007-0.022	0.82	0.81-0.85
Sheep milk	0.12	0.06	0.06-0.2	0.78	0.76-0.8
Goat milk	0.12	0.07	0.07-0.32	0.8	0.81-0.87
Beef meat	0.013	0.11	0.08-0.02	0.66	0.64-0.69
Veal	0.03	0.08	0.06-0.15	0.69	0.64-0.72
Mutton	0.13	0.1	0.1-0.5	0.46	0.53-0.52
Lamb	0.2	0.08	0.1-0.4	0.78	0.75-0.81
Goat meat	0.2	0.1	0.1-0.4	0.67	0.62-0.72
Pork	0.06	0.13	0.04-0.1	0.58	0.59-0.62
Hen meat	2.7	0.1	2-4	0.6	0.57-0.63
Chicken	3.0	0.1	2-4	0.6	0.55-0.65
Egg	2.1	0.08	1.6-3	0.66	0.63-0.7

Table 7

Transfer coefficients for OBT intake estimated using the approach of Galeriu et al. (2001).

Animal product	F_{OBT} $d\ l^{-1}$ or $d\ kg^{-1}$	*Fraction OBT*	F_{OBT} *range*	CR_{OBT}	CR_{OBT} *range*
Cow milk	0.017	0.47	0.01-0.03	0.24	0.22-0.37
Sheep milk	0.18	0.57	0.05-0.2	0.32	0.23-0.39
Goat milk	0.13	0.4	0.1-0.45	0.32	0.25-0.38
Beef meat	0.042	0.8	0.03-0.07	0.4	0.35-0.44
Veal	0.07	0.72	0.06-0.15	0.35	0.31-0.4
Mutton	0.33	0.75	0.2-0.5	0.4	0.35-0.44
Lamb	0.38	0.67	0.2-0.6	0.38	0.35-0.4
Goat meat	0.2	0.67	0.1-0.5	0.43	0.4-0.46
Pork	0.19	0.73	0.13-0.4	0.52	0.5-0.68
Hen meat	4.0	0.6	3-4	0.7	0.67-0.74
Chicken	5.8	0.57	4-8	0.6	0.57-0.63
Egg	4.4	0.78	3.4-5	0.64	0.62-0.69

Table 8

Results of limited example sensitivity study for tritium transfer to dairy cattle and chickens applying the model of Galeriu et al. (2001).

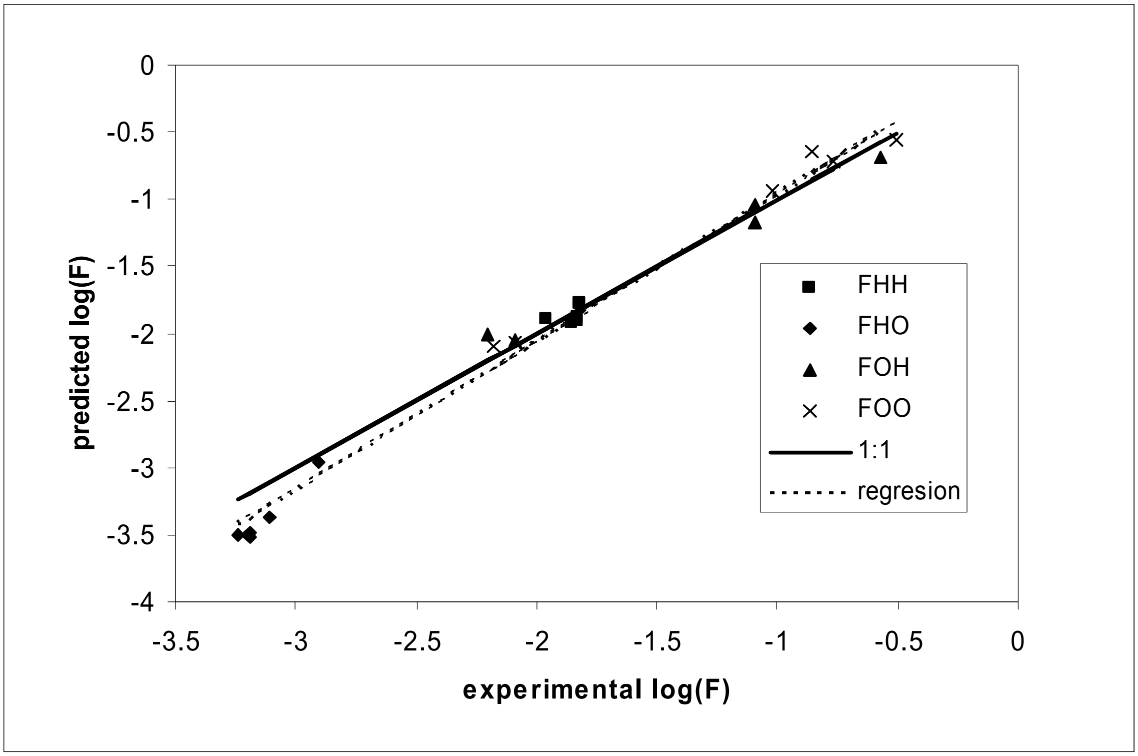
Parameter value	Water Intake (kg d^{-1})	DM intake (kg d^{-1})	F_{HH}	F_{OH}	F_{HO}	F_{OO}	CR_{HTO}	CR_{OBT}
Milk yield (kg d^{-1})								
5	39.4	8.8	2.04E-02	1.41E-02	5.18E-04	1.39E-02	8.24E-01	2.45E-01
15	62.8	14.0	1.28E-02	8.86E-03	3.25E-04	8.72E-03	8.24E-01	2.45E-01
40	121	27.0	6.62E-03	4.59E-03	1.68E-04	4.51E-03	8.24E-01	2.45E-01
Range*			0.32	0.32	0.32	0.32	1.00	1.00
Live- weight (kg)								
350	54.8	12.2	1.46E-02	1.02E-02	3.73E-04	9.98E-03	8.24E-01	2.45E-01
550	62.8	14.0	1.28E-02	8.86E-03	3.25E-04	8.72E-03	8.24E-01	2.45E-01
750	70.1	15.6	1.15E-02	7.95E-03	2.92E-04	7.81E-03	8.24E-01	2.45E-01
Range			0.78	0.78	0.78	0.78	1.00	1.00
Water : DM intake								
4	55.8	14.0	1.43E-02	9.88E-03	3.62E-04	8.74E-03	8.16E-01	2.60E-01
4.5	62.8	14.0	1.28E-02	8.86E-03	3.25E-04	8.72E-03	8.24E-01	2.45E-01
7	97.7	14.0	8.45E-03	5.86E-03	2.15E-04	8.64E-03	8.47E-01	2.02E-01
Range			0.59	0.59	0.59	0.99	1.04	0.78
Diet digestibility								
0.5	62.8	14.0	1.30E-02	6.52E-03	3.32E-04	6.29E-03	8.22E-01	1.75E-01
0.72	62.8	14.0	1.30E-02	9.40E-03	3.32E-04	9.06E-03	8.22E-01	2.52E-01
1	62.8	14.0	1.30E-02	1.30E-02	3.32E-04	1.26E-02	8.22E-01	3.50E-01
Range			1.00	2.00	1.00	2.00	1.00	2.00
Milk Fat								
3	58.2	12.9	1.38E-02	9.56E-03	3.51E-04	9.17E-03	8.24E-01	2.45E-01
4	62.8	14.0	1.28E-02	8.86E-03	3.25E-04	8.50E-03	8.24E-01	2.45E-01
5	67.4	15.0	1.19E-02	8.26E-03	3.03E-04	7.92E-03	8.24E-01	2.45E-01
Range			1.16	1.16	1.16	1.16	1.00	1.00
SAR								
0.2	62.8	14.0	1.28E-02	8.86E-03	2.60E-04	8.50E-03	8.20E-01	2.53E-01
0.25	62.8	14.0	1.28E-02	8.86E-03	3.25E-04	8.50E-03	8.24E-01	2.45E-01
0.3	62.8	14.0	1.28E-02	8.86E-03	3.90E-04	8.50E-03	8.28E-01	2.38E-01
Range			1.00	1.00	0.67	1.00	0.99	1.06

* Range is the minimum to maximum ratio

Table 9

Preliminary concentration ratios for horse, yak and camel

Animal product	^{14}C	*HTO*	*OBT*
Horse milk	0.11	0.9	0.33
Horse meat	0.33	0.74	0.42
Yak milk	0.27	0.81	0.32
Yak meat	0.41	0.71	0.40
Camel milk	0.17	0.87	0.42
Camel meat	0.29	0.77	0.48



predicted log(F)
experimental log(F)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
FHH
FHO
FOH
FOO
1:1
regresion

Fig. 1

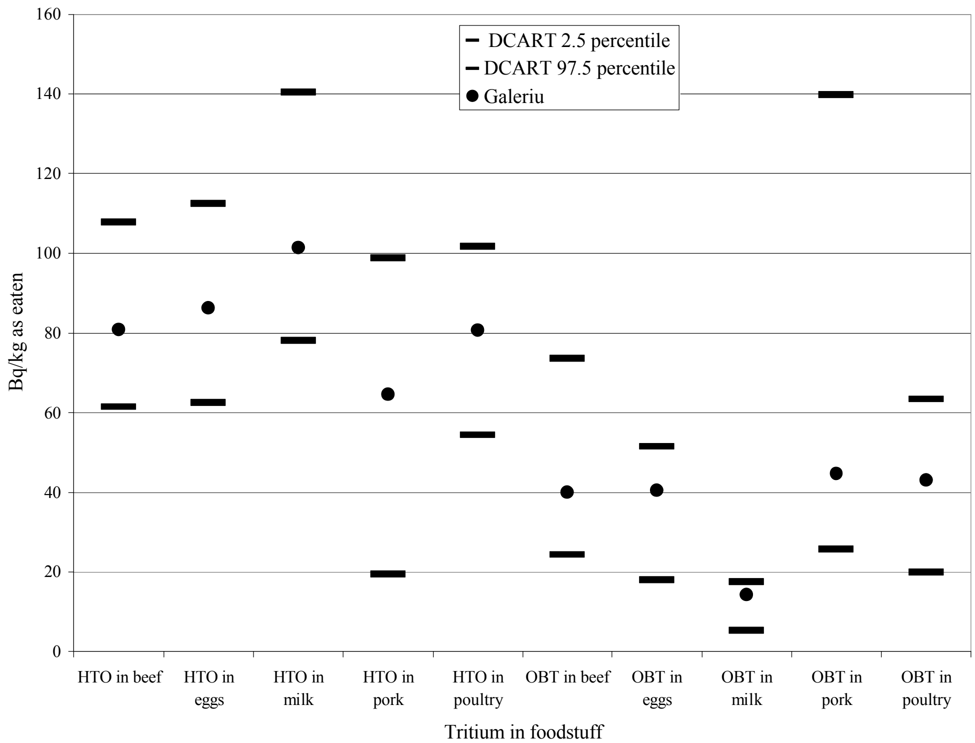

DCART 2.5 percentile
DCART 97.5 percentile
Galeriu
Bq/kg as eaten
0
20
40
60
80
100
120
140
160
HTO in beef
HTO in eggs
HTO in milk
HTO in pork
HTO in poultry
OBT in beef
OBT in eggs
OBT in milk
OBT in pork
OBT in poultry
Tritium in foodstuff

Fig. 2